

High-redshift galaxies in the *Hubble Deep Field*: colour selection and star formation history to $z \sim 4$

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Accepted 1996 August 15. Received 1996 August 1; in original form 1996 July 10

ABSTRACT

The Lyman decrement associated with the cumulative effect of H I in QSO absorption systems along the line of sight provides a distinctive feature for identifying galaxies at $z \gtrsim 2.5$. Colour criteria, which are sensitive to the presence of a Lyman continuum break superposed on an otherwise flat UV spectrum, have been shown, through Keck spectroscopy, to successfully identify a substantial population of star-forming galaxies at $3 \lesssim z \lesssim 3.5$. Such objects have proven to be surprisingly elusive in field galaxy redshift surveys; quantification of their surface densities and morphologies is crucial for determining how and when galaxies formed. The *Hubble Deep Field* (*HDF*) observations offer the opportunity to exploit the ubiquitous effect of intergalactic absorption and obtain useful statistical constraints on the redshift distribution of galaxies to considerably fainter limits than the current spectroscopic limits. We model the H I cosmic opacity as a function of redshift, including scattering in resonant lines of the Lyman series and Lyman continuum absorption, and use stellar population synthesis models with a wide variety of ages, metallicities, dust contents and redshifts to derive colour selection criteria that provide a robust separation between high-redshift and low-redshift galaxies. From the *HDF* images we construct a sample of star-forming galaxies at $2 \lesssim z \lesssim 4.5$. While none of the ~ 60 objects in the *HDF* having known Keck/Low-Resolution Imaging Spectrograph (LRIS) spectroscopic redshifts in the range $0 \lesssim z \lesssim 1.4$ is found to contaminate our high-redshift sample, our colour criteria are able to efficiently select the $2.6 \lesssim z \lesssim 3.2$ galaxies identified by Steidel et al.

The ultraviolet (and blue) dropout technique opens up the possibility of investigating cosmic star and element formation in the early Universe. We set a lower limit to the ejection rate of heavy elements per unit comoving volume from Type II supernovae at $\langle z \rangle = 2.75$ of $\approx 3.6 \times 10^{-4} M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ (for $q_0 = 0.5$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$), which is 3 times higher than the local value but still 4 times lower than the rate observed at $z \approx 1$. At $\langle z \rangle = 4$, our lower limit to the cosmic metal ejection rate is ≈ 3 times lower than the $\langle z \rangle = 2.75$ value. We discuss the implications of these results on models of galaxy formation, and on the chemical enrichment and ionization history of the intergalactic medium.

Key words: stars: formation – galaxies: evolution – intergalactic medium – quasars: absorption lines – cosmology: observations – ultraviolet: galaxies.

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1 INTRODUCTION

Much observing time has been devoted in the past few years to the problem of the detection of galaxies at high redshift, as it is anticipated that any knowledge of their early luminosity and colour evolution will put constraints on the history of structure and metal formation. While it has become clear that blank-sky surveys for strong Ly α -emitting primeval galaxies are not particularly efficient (e.g., Pritchet & Hartwick 1990, Djorgovski & Thompson 1993), the method of obtaining multicolour broad-band observations of the rest-frame UV stellar continuum of the emitter has been successfully applied to detect galaxies at cosmological distances (Steidel et al. 1996a).

Ground-based observations have used colour techniques that are sensitive to the presence of a Lyman continuum break to identify or set limits on the number of high-redshift galaxies (Steidel & Hamilton 1992, 1993). The signature of a distant, star-forming galaxy in such surveys is a very red $U-B$ colour, combined with colours in longer wavelength filters that are much bluer. The early work by Guhathakurta, Tyson & Majewski (1990) showed that Lyman break objects do not dominate the galaxy counts at faint apparent magnitudes. Assuming that young, star-forming galaxies have flat spectra longward of the Lyman break, Steidel & Hamilton (1992, 1993), and Steidel, Pettini & Hamilton (1995) have designed and used a custom set of broad-band filters to select high-redshift galaxies in the fields of distant QSOs. Recent deep spectroscopy with the W. M. Keck telescope has shown the high efficiency of such a colour-selection technique: Steidel et al. (1996a) have identified 17 Lyman break star-forming galaxies with redshifts $3.0 \lesssim z \lesssim 3.5$, which are most likely the progenitors of the present-day bright spirals and ellipticals observed during the assembly of their cores (Giavalisco, Steidel & Macchetto 1996).

With its high spatial resolution, the *Hubble Space Telescope* (*HST*) offers the opportunity to study the faint galaxy population in unprecedented detail. In particular, the images of the *Hubble Deep Field* (*HDF*), obtained with the Wide Field and Planetary Camera (WFPC-2) during 1995 December, represent the deepest optical imaging survey undertaken so far (Williams et al. 1996), reaching 5σ limiting AB magnitudes of roughly 27.7, 28.6, 29.0 and 28.4 (for an aperture area of 0.2 arcsec^2) in the F300W, F450W, F606W and F814W bandpasses (the number corresponds to the central wavelength in nm), respectively. In this paper, we describe selection criteria for this filter system that can be used to identify a sample of likely precursors to present-day galaxies at $z > 2$, with little contamination from low-redshift galaxies. Our strategy is designed to exploit the effect of the increasing opacity of the intergalactic medium (IGM) at high redshifts, as indicated by the plethora of absorption lines seen in the spectra of background quasars: enough neutral hydrogen is known to be contained in the clumps of highly ionized gas that form the Ly α forest, and in the metal-line absorption systems associated with the halo regions of intervening bright galaxies, to significantly attenuate the UV flux from distant sources. We show that the cumulative effect of H I in QSO absorption systems along the line of sight provides a distinctive feature for identifying star-forming galaxies in the *HDF*. Although other spectral

features, such as the 4000- and 912-Å breaks which characterize the integrated spectra of stellar populations, with the latter possibly enhanced by self-absorption from interstellar gas within the galaxy itself, may also be used as tracers of redshifts, the model predictions of their magnitude are sensitive to the unknown physical and evolutionary state of the galaxy, i.e., its star formation history, age and H I distribution, and hence are subject to substantial uncertainties. By contrast, the ‘reddening’ effect due to atomic processes in cosmological distributed QSO absorption systems is ubiquitous, quite strong for $z \gtrsim 2.5$, and can be reliably taken into account. Although stochastic in nature, rms fluctuations away from the mean opacity are bound to be modest in most situations, due to the broad-band nature of the adopted filter set.

The technique used to analyse the *HDF* images we develop in this paper is based on the theoretical study by Madau (1995) (see also Yoshii & Peterson 1994), and is an extension of the Lyman break colour criterion developed by Steidel & Hamilton (1992, 1993), and Steidel et al. (1995). We extend this technique to the *HDF* filter system, and perform several experiments with simulated and real galaxy spectra to define effective selection criteria for high-redshift galaxies, and identify possible sources of contamination from low redshifts. By computing colours for an extremely wide range of model galaxy spectra, we are able to tune the criteria to provide what we believe are largely uncontaminated samples of star-forming galaxies in the redshift ranges $2 < z < 3.5$ and $3.5 < z < 4.5$, and use these samples to estimate the integrated star formation and metal ejection rates at those redshifts. We show how follow-up spectroscopy with Keck/LRIS by Steidel et al. (1996b), the Hawaii + Caltech group (Cohen et al. 1996) and the Berkeley *HDF* group (Moustakas, Zepf & Davis 1996) supports the efficiency of our colour selection techniques. Future work on high-redshift galaxies in the *HDF* will investigate the luminosity function, study the morphologies, and compare the numbers and properties of high-redshift candidates to the predictions of a variety of galaxy evolution models.

Throughout this paper, unless otherwise stated, we shall adopt a flat cosmology with $q_0 = 0.5$ and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 INTERGALACTIC ATTENUATION

In this section we will briefly review the theory of the propagation of UV radiation through a clumpy universe, following Madau (1995).

2.1 Basic equations

Let $L(\nu_{\text{em}})$ be the specific power emitted with frequency ν_{em} by a source at redshift z_{em} . The mean specific flux observed at Earth is

$$\langle f(\nu_{\text{obs}}) \rangle = \frac{(1+z_{\text{em}})L(\nu_{\text{em}})}{4\pi d_L^2} \langle e^{-\tau} \rangle, \quad (1)$$

where $\nu_{\text{obs}} = \nu_{\text{em}}/(1+z_{\text{em}})$, d_L is the luminosity distance to z_{em} and the average transmission over all lines of sight is, assuming Poisson-distributed clouds,

$$\langle e^{-\tau} \rangle = \exp \left\{ \int_0^{z_{\text{em}}} \int \frac{\partial^2 N}{\partial N_{\text{H I}} \partial z} [1 - e^{-\tau_c}] dN_{\text{H I}} dz \right\}. \quad (2)$$

Here, τ_c is the optical depth through an individual cloud at frequency $\nu = \nu_{\text{obs}}(1+z)$, and $(\partial^2 N / \partial N_{\text{H I}} \partial z)$ is the redshift and column density distribution of absorbers along the path. An ‘effective’ optical depth of a clumpy medium can be defined as $\tau_{\text{eff}} = -\ln(\langle e^{-\tau} \rangle)$.

Along with resonant line scattering from Ly α , β , γ and higher order members, we include photoelectric absorption from H I in the Ly α forest clouds and Lyman limit systems along the line of sight. Since the bluest filter used for the *HDF* observations is centred at 3000 Å and has FWHM ~ 800 Å, galaxies will only be subject to H I cosmological attenuation from material located at $z \gtrsim (2600/1216) - 1 = 1.1$.

2.2 Line blanketing and continuum absorption

For $\lambda_\beta(1+z_{\text{em}}) < \lambda_{\text{obs}} < \lambda_\alpha(1+z_{\text{em}})$, where $\lambda_\alpha = 1216$ Å and $\lambda_\beta = 1026$ Å, the continuum intensity of a galaxy is attenuated by the combined blanketing effect of many Ly α forest absorption lines, with effective opacity

$$\tau_{\text{eff}} = 0.0036 \left(\frac{\lambda_{\text{obs}}}{\lambda_\alpha} \right)^{3.46}, \quad (3)$$

(Press, Rybicki & Schneider 1993). Hence, line blanketing from Ly α alone will produce $\gtrsim 1$ mag of attenuation in the continuum spectrum shortward of 6000 Å of a galaxy at $z_{\text{em}} \gtrsim 4$.

When $\lambda_{\text{obs}} \leq \lambda_\beta(1+z_{\text{em}})$, a significant contribution to the blanketing opacity comes from the higher order lines of the Lyman series. A standard curve of growth analysis has been applied to numerically compute the attenuation expected from line blanketing of Ly β , γ , δ plus 13 higher order members. In the wavelength range $\lambda_{i+1}(1+z_{\text{em}}) < \lambda_{\text{obs}} < \lambda_i(1+z_{\text{em}})$, the total optical depth can be written as the sum of the contributions from the $j \rightarrow i$ transitions,

$$\tau_{\text{eff}} = \sum_{j=2,i} A_j \left(\frac{\lambda_{\text{obs}}}{\lambda_j} \right)^{3.46}, \quad (4)$$

where $A_j = (1.7 \times 10^{-3}, 1.2 \times 10^{-3}, 9.3 \times 10^{-4})$ and $\lambda_j = (1026, 973, 950 \text{ Å})$ for Ly β , γ and δ , respectively. It is worth noting that heavy element absorbers make a negligible contribution to the blanketing optical depth at high redshifts, as this is dominated by those lines that lie at the transition between the linear and the flat part of the curve of growth, i.e., with $N_{\text{H I}} \approx 10^{13.6} \text{ cm}^{-2}$ in the case of Ly α .

Continuum absorption by H I affects photons observed at $\lambda_{\text{obs}} < \lambda_{\text{L}}(1+z_{\text{em}})$, where $\lambda_{\text{L}} = 912$ Å is the Lyman limit. An approximate (within 5 per cent) integration of equation (2) yields, for the effective photoelectric optical depth along the line of sight,

$$\tau_{\text{eff}} = 0.25x_c^3(x_{\text{em}}^{0.46} - x_c^{0.46}) + 9.4x_c^{1.5}(x_{\text{em}}^{0.18} - x_c^{0.18}) - 0.7x_c^3(x_{\text{em}}^{-1.32} - x_c^{-1.32}) - 0.023(x_{\text{em}}^{1.68} - x_c^{1.68}), \quad (5)$$

where $x_c = (\lambda_{\text{obs}}/\lambda_{\text{L}})$ for $\lambda_{\text{obs}} > \lambda_{\text{L}}$, and $x_{\text{em}} = 1 + z_{\text{em}}$. The first term on the right-hand side represents the approximate contribution of Ly α clouds, the others are due to Lyman

limit systems. Absorbers with $N_{\text{H I}} \sim 10^{17} \text{ cm}^{-2}$ dominate the cosmic continuum opacity.¹

While our formula for the line blanketing optical depth is entirely consistent with the flux deficits D_A and D_B observed in the spectra of QSOs below their Ly α and Ly β emission features (e.g., Schneider, Schmidt & Gunn 1991), the derived continuum opacity is subject to significant uncertainties, as very limited information exists on optically thin absorbers with $10^{16} \lesssim N_{\text{H I}} \lesssim 10^{17} \text{ cm}^{-2}$.

2.3 Cosmic transmission

Fig. 1(a) shows the characteristic staircase profile (cf. Møller & Jakobsen 1990) of the mean cosmic transmission $\langle e^{-\tau} \rangle$ for a source at $z_{\text{em}} = 3, 4$ and 5, as a function of observed wavelength. Also plotted are the response functions of the photometric system we will adopt in our discussion. This consists of the four broad *HST* passbands F300W, F450W, F606W and F814W (roughly *UBVI*). These filters efficiently cover most of the bandpass accessible to the *HST* WFPC-2.

It is clear that the observed broad-band colours of cosmological distant objects will be strongly ‘reddened’ by continuum absorption and blanketing of discrete absorption lines that move into and out of the colour passbands with changing z . To be quantitative, we must take into account that the mean transmission observed is not $\langle e^{-\tau} \rangle$ but rather an average over the bandpass,

$$Q(z_{\text{em}}) = \int e^{-\tau_{\text{eff}}(\lambda)} T(\lambda) d\lambda, \quad (6)$$

where $T(\lambda)$ is the normalized transmittance of the relevant filter. In the following, we will measure the mean integrated intergalactic attenuation in magnitudes, $\Delta m = -1.086 \ln Q$. Fig. 1(b) shows ΔU_{300} , ΔB_{450} , ΔV_{606} and ΔI_{814} , the observed magnitude increases at the corresponding bandpass due to intervening absorption, as a function of emission redshift in the redshift range $1.5 < z < 5$. [These increments must be added to the term $-1.086 \ln(1+z_{\text{em}})$ to get the standard K -correction for a flat emitted spectrum.]

We are now able to assess how intergalactic absorption will modify the intrinsic photometric properties of galaxies at high redshift. At $z_{\text{em}} \approx 1.5$, Ly α line blanketing starts to cause a small apparent depression in the U_{300} -band continuum. As higher order lines of the Lyman series move into the bandpass, ΔU_{300} increases rapidly until, at $z_{\text{em}} = 2.3$, sources in the background appear, on average, ≈ 0.7 mag fainter in the ultraviolet. By $z_{\text{em}} = 3$, Lyman continuum absorption from forest clouds and Lyman limit systems is so severe that $\Delta U_{300} \approx 2.8$ mag (of which ≈ 1.9 mag are due to Ly α cloud alone): galaxies will either appear very red in $U_{300} - B_{450}$ or will drop out of the F300W image altogether.² Similarly, the Ly α line progressively enters the F450W band beyond $z_{\text{em}} \approx 2.7$. At $z_{\text{em}} = 3.8$, line blanketing from the

¹The He I contribution to the attenuation is negligible in the case of a QSO-dominated ionizing background, while He II absorption on the way must be included if $(1+z_{\text{em}}) > \lambda_{\text{obs}}/228$ Å (e.g., Madau 1992).

²Note that ΔU_{300} flattens for $z_{\text{em}} \gtrsim 3.6$ because of a significant ‘red leak’ of the F300W filter above 6700 Å.

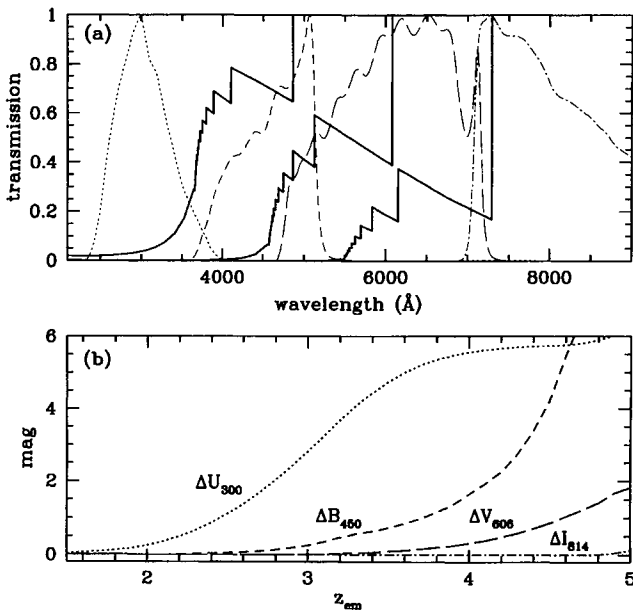


Figure 1. (a) Mean cosmic transmission for a source at $z_{em} = 3, 4$ and 5 (solid lines), as a function of observed wavelength. The characteristic staircase profile is due to continuum blanketing from the Lyman series. Also plotted are the response functions of the four broad passbands, F300W (dotted line), F450W (short-dashed line), F606W (long-dashed line) and F814W (dash-dotted line) used for the *Hubble Deep Field*. (b) Magnitude increments ΔU_{300} (dotted line), ΔB_{450} (short-dashed lines), ΔV_{606} (long-dashed line) and ΔI_{814} (dash-dotted line), derived by integrating the mean cosmic transmission over the corresponding bandpass, as a function of the emission redshift.

Lyman series produces $\Delta B_{450} \approx 1.2$ mag. By $z_{em} = 4.4$, Lyman continuum absorption contributes significantly to the total opacity, and ΔB_{450} exceeds 3.3 mag. The F606W bandpass is only weakly affected by intergalactic absorption for $z_{em} \lesssim 4$. Hence, again, star-forming galaxies at $z_{em} \sim 4$ will either appear very red in $B_{450} - V_{606}$ or will effectively be undetectable in the blue band. By $z_{em} = 4.6$, line blanketing from the Lyman series produces $\Delta V_{606} \approx 1$ mag. As H I absorption does not affect the F814W passband for $z_{em} \lesssim 5.7$, $\Delta I_{814} = 0$ in the redshift range of interest here.

Although Fig. 1(b) refers to the average accumulated absorption only, rms fluctuations away from the mean transmission are predicted to be relatively small after integration over broad bandpasses (Press et al. 1993). For example, the observed B_{450} -band continuum of a galaxy at $z_{em} \gtrsim 3$ is attenuated by the blanketing of more than 90 Ly α lines with $W > 0.3$ Å along the light travel path. At these redshifts, excursions away from the average curve will be the largest in the F300W filter, due to the contribution to the photoelectric opacity by the rarer, optically thick Lyman limit systems. Even in this case, however, with $dN/dz \approx 0.27(1+z)^{1.55}$ absorbers per unit redshift with $N_{H I} > 1.6 \times 10^{17} \text{ cm}^{-2}$ (Storrie-Lombardi et al. 1994), as many as $\Delta N \sim 1.5$ Lyman limit systems along a random path to $z_{em} \gtrsim 2.7$ would be expected, on average, to photoelectrically absorb photons in the ultraviolet bandpass. As the probability of intersecting at least one metal system is large, $1 - e^{-\Delta N} \approx 80$ per cent, we expect only one out of five

star-forming galaxies at $z > 2.7$ to be effectively detectable in the ultraviolet bandpass.

3 THE COLOURS OF HIGH-REDSHIFT GALAXIES

One of the major objectives of the *HDF* observations is to determine the morphology, spectral energy distribution and number density of galaxies actively forming stars at high-redshift, the nature of which is crucial to our understanding of galaxy evolution. In this section we will show how we can use intergalactic absorption to identify high-redshift galaxies in broad-band multicolour surveys. Colours can be more readily interpreted using the *AB*-magnitude system (Oke 1974):

$$m_{AB} = -2.5 \log \int f(\nu) e^{-\tau_{eff}} T(\nu) d\nu - 48.6, \quad (7)$$

where $f(\nu) e^{-\tau_{eff}}$ is the mean incident power measured in $\text{erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$. We put our magnitudes directly into the *AB* system, so that $U_{300} = B_{450} = V_{606} = I_{814}$ corresponds to a spectrum for which $f(\nu) e^{-\tau_{eff}}$ is constant. The observed colours of distant objects are determined by the intrinsic spectral energy distributions (SEDs) of their stellar populations, absorption and scattering of photons in their interstellar media, and stochastic absorption due to intervening H I clouds. Because we do not know when galaxies started forming stars, and over what time-scale they formed them, it is impossible to predict their energy distribution in detail. Furthermore, it is not necessarily the case that the faintest galaxies are the most distant. Thus our analysis must not rely on fluxes or apparent magnitudes to give redshift information. It is, however, possible to outline in a general way the range of plausible colours for star-forming galaxies at high redshift, and to identify combinations of age and dust reddening in a stellar population at lower redshift that may conspire to mimic a high-redshift galaxy.

3.1 The spectral energy distribution of star-forming galaxies

For illustrative purposes, we analyse here two simple examples in detail.

(1) We compute the ultraviolet spectrum of a star-forming galaxy using the isochrone synthesis spectral evolutionary code of Bruzual & Charlot (1993). The model has solar metallicity, a constant star formation rate at age 0.3 Gyr, a Salpeter (1955) initial mass function (IMF), $\phi(m) \propto m^{-2.35}$, with lower and upper cut-offs of 0.1 and 125 M_{\odot} , respectively, and completely ignores the effects of H I in the local interstellar medium on the transfer of ionizing photons. Two intrinsic discontinuities, about 1.4 mag across the rest-frame Lyman limit and 0.5 mag across the Balmer decrement, are characteristic of the most prominent stars.

(2) We take as fiducial the spectra of the four brightest starburst galaxies observed by the Hopkins Ultraviolet Telescope (HUT) on board *Astro-2*: NGC 3310, 4214, 5236 and 5253 (Ferguson et al., in preparation). The HUT spectra cover the wavelength range $912 < \lambda < 1820$ Å (Kruk et al.

1995). The cut-off at short wavelengths is due to galactic H I. For wavelengths longward of 1820 Å, we have patched on the *IUE* spectra from the Kinney et al. (1993) atlas, renormalized to the HUT flux in the range 1350–1700 Å. The renormalization is required because of the different sizes of the HUT and *IUE* apertures. Note that the starburst galaxy intrinsic colours are significantly redder than the ones derived from the population synthesis model because of the presence of a large Lyman discontinuity and of dust reddening. HUT spectra of somewhat more distant starburst galaxies suggest that the intrinsic Lyman break is typically at least a factor of 5 (Leitherer et al. 1995). Analysis of the NGC 5236 HUT SED suggests that a young ($\sim 5 \times 10^6$ year old) population is responsible for the emission, with an intervening extinction $E(B-V) \approx 0.2$ necessary to fit the detailed SED (Ferguson et al., in preparation). Such a modest extinction appears fairly typical of starburst galaxies (even those of high metallicity). In a comprehensive study of 39 starburst galaxies, Calzetti, Kinney & Storchi-Bergmann (1994) found values of $E(B-V)$ ranging from 0 to 0.8.

Fig. 2(a) displays the predicted $U_{300}-B_{450}$, $B_{450}-V_{606}$ and $V_{606}-I_{814}$ colours versus emission redshift of our synthetic IGM-attenuated galaxy, together with the unattenuated values. The intrinsic spectral shape has been kept constant with cosmic time. As expected, the observed colours redden quite sharply with redshift due to intergalactic absorption. For example, from $z_{\text{em}}=2.5$ to $z_{\text{em}}=3$, the observed $U_{300}-B_{450}$ colour of the Bruzual spectrum increases from

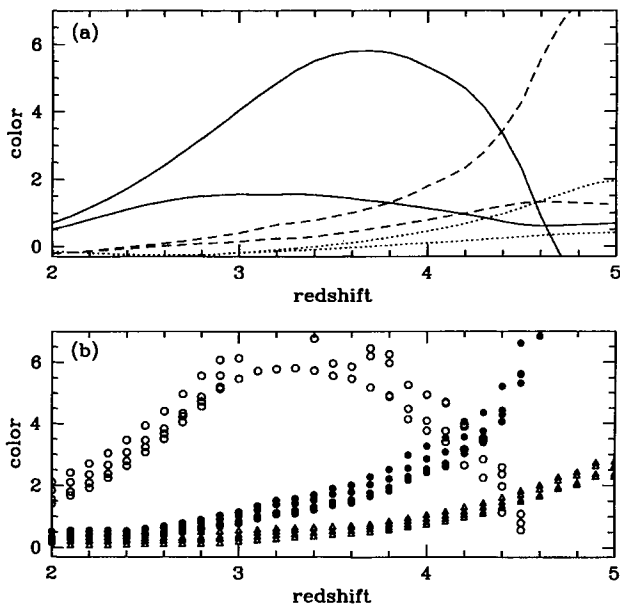


Figure 2. (a) Apparent synthetic colours of a star-forming galaxy with constant SFR (age 0.3 Gyr) plotted as a function of the emission redshift. Each pair of curves depicts from top to bottom the attenuated colours and the colours observed in the case of negligible intergalactic absorption, respectively. Solid lines: $U_{300}-B_{450}$. Dashed line: $B_{450}-V_{606}$. Dotted lines: $V_{606}-I_{814}$. (b) The colours of the four brightest starburst galaxies observed by HUT (see text for details). Empty dots: $U_{300}-B_{450}$. Filled dots: $B_{450}-V_{606}$. Triangles: $V_{606}-I_{814}$. All spectra have been reddened by intergalactic absorption.

1.8 to 3.6 mag. In the absence of any absorption break, the last value would correspond to a spectral energy distribution $f(\nu) \propto \nu^{-\alpha}$ with $\alpha=8$.³ The observed flux decrements between 4500 and 6060 Å and between 6060 and 8140 Å similarly probe the universe at higher and higher redshifts, as $B_{450}-V_{606}$ increases from 0.8 at $z_{\text{em}}=3.5$ to 1.7 mag at $z_{\text{em}}=4$, while $V_{606}-I_{814}$ increases from 1.0 at $z_{\text{em}}=4.5$ to 1.9 mag at $z_{\text{em}}=5$. A similar plot is shown in Fig. 2(b) for the observed HUT-*IUE* starburst galaxy spectra. The main point to note here is how intrinsically blue and red objects follow similar paths in the colour-redshift plane, and that, even in the presence of dust reddening, *the large magnitude jumps between adjacent bandpasses are largely caused by the known sources of intergalactic H I opacity – the Ly α clouds and Lyman limit systems – rather than by the assumed galaxy SED.*

3.2 Colour selection criteria

The problem of identifying high-redshift galaxies is complicated by the fact that the present-day colours and spectra of galaxies allow for a very wide variety of star-formation histories. This evolution is coupled with chemical evolution of the stars and the ISM and changes in the amount of dust and its distribution relative to the stars. However, galaxy spectra are not entirely arbitrary. Flux is usually a slowly varying function of wavelength, with a few spectral discontinuities (e.g., the 4000- and 912-Å breaks) at specific locations. Thus it should be possible to construct fairly robust selection criteria that will exploit the combined effect of the intrinsic Lyman edge in galaxies and the opacity of intergalactic neutral hydrogen to separate high-redshift objects from low-redshift objects.

In this section, we will define criteria appropriate to the *HDF* bandpasses. To derive a robust colour selection technique, we have computed *HDF* colours for 1612 synthetic spectra of galaxies, representing different ages, star formation histories, metallicities and dust opacities. The stellar evolutionary input to the models has been described in detail by Babul & Ferguson (1996). Briefly, synthetic spectra are computed using isochrone synthesis from the isochrones of Bertelli et al. (1994), and the model atmospheres of Kurucz (1992, private communication) and Clegg & Middlemass (1987). The synthetic spectra agree well with those of Bressan, Chiosi & Fagotto (1994), which were constructed using the same isochrones, and slightly less well with those of Bruzual & Charlot (1993), primarily due to their use of different isochrones. The uncertainties in population synthesis have been outlined in some detail by Charlot, Worthey & Bressan (1996). These uncertainties amount to differences in colour of several tenths for the same stellar population computed by different codes. While they can cause very large discrepancies in the derived ages, such small variations in colour are almost completely negligible for our purposes.

Attenuation by dust has been included using the parametrized extinction laws of Pei (1992) for the Galaxy, the

³Above $z_{\text{em}} \approx 3.5$, $U_{300}-B_{450}$ becomes bluer, again an effect of the red leak of the F300W filter. By then, however, intergalactic attenuation is so strong that high-redshift galaxies are effectively unobservable in the ultraviolet.

Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). Note that the use of the relatively ‘grey’ extinction curve for starburst galaxies found by Calzetti et al. (1994) would imply a higher UV continuum than that predicted on the basis of the optical continuum emission by the application of the standard extinction laws, hence strengthening the efficiency of our selection criteria. We ignore the effects of H I in the local interstellar medium of the galaxies, which will add to the intergalactic attenuation to make high-redshift objects even redder. There are no emission lines included in the simulations. Given the very wide bandpasses of the *HDF* filters, we do not expect emission lines to significantly alter galaxy broad-band colours.

The colours for the models have been computed at 73 different redshifts spanning the interval $0.001 < z < 7$, taking into account the effect of intergalactic attenuation. In this exercise, galaxies are required to be younger than the age of the universe (for $q_0 = 0.5$, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$), but otherwise age has been decoupled from redshift. The model grid is intended to span the range of plausible colours of real galaxies, but not to sample this range in a way that is tied to cosmological models. For example, in the real Universe we expect the old, low-redshift portion of a colour–colour diagram to be more densely populated than in our simulations. The adopted grid of ages, star formation time-scales, extinctions A_B and redshifts is summarized in Table 1. It is important to emphasize that our goal is to construct a *robust* set of colour selection criteria that are *largely independent* of models of galaxy formation or the assumed values of the cosmological parameters. In this respect our approach is quite distinct from efforts to assign photometric redshifts to each galaxy, as presented by Lanzetta, Yahil & Fernández-Soto (1996) and Gwyn & Hartwick (1996), for example.

3.2.1 F300W dropouts

We are now in a position to examine the colours of arbitrary galaxies as a function of redshift. Fig. 3 shows $U_{300} - B_{450}$ versus $B_{450} - I_{814}$ for all of the synthetic spectra. The large points show objects with $2 < z < 3.5$. Galaxies in this redshift range predominantly occupy the top left portion of the plot because of the attenuation by the IGM and intrinsic extinction. Galaxies at lower redshift can have similar $U_{300} - B_{450}$ colours, but they are typically either old or dusty, and are therefore red in $B_{450} - I_{814}$ as well. To identify likely star-forming galaxies in our desired redshift range, we require that they have (1) $U_{300} - B_{450} > 1.3$, (2)

$U_{300} - B_{450} > B_{450} - I_{814} + 1.2$ and (3) $B_{450} - I_{814} < 1.5$. These criteria isolate objects that have relatively blue colours in the optical, but a sharp drop into the UV.

Fig. 4 gives an estimate of the efficiency of this technique. The solid histogram shows the fraction of the total sample of models that meet the selection criteria as a function of redshift. Even with the wide range of parameters in our galaxy models, *no* galaxies with $z < 1.5$ or $z > 4$ are selected. However, many of the galaxies in the redshift range $2 < z < 4$ are missed as well. The galaxies that are missed tend to be redder than the selection line in $B_{450} - I_{814}$, either because they are relatively old or because they are highly reddened by dust. The dotted histogram in Fig. 4 shows the selection efficiency for galaxies with ages restricted to be less than 10^8 yr and extinctions $A_B < 2$. The selection criteria appear to be extremely efficient, recovering roughly 90 per cent of the galaxies in the redshift range $2 < z < 3.5$. Of course the true efficiency depends on how close our models are to real protogalaxies, and on how many old or very dusty galaxies there are in the real Universe in that redshift range.

3.2.2 F450W dropouts

We can play an identical game with the F450W dropouts. Fig. 5 shows the colours of the model galaxies in the $B_{450} - V_{606}$ versus $V_{606} - I_{814}$ plane, with galaxies in the redshift range $3.5 < z < 4.5$ highlighted, and with our proposed selection criteria drawn. In this case, there are objects outside the redshift range of interest that can have rather blue $V_{606} - I_{814}$ colours and red $B_{450} - V_{606}$ colours, and hence potentially contaminate the sample. These peculiar colours are obtained only for those galaxies that lie in the redshift range $2 < z < 3.5$ and have a fair amount of internal extinction. The blue $V_{606} - I_{814}$ colour is due to the 2200-Å absorption feature shifting into the F814W bandpass. Our selection criteria are tuned to avoid including many of these galaxies. Specifically, we require our candidates to have (1) $B_{450} - V_{606} > 1.5$, (2) $B_{450} - V_{606} > 1.7(V_{606} - I_{814}) + 0.7$, (3) $B_{450} - V_{606} < 3.5(V_{606} - I_{814}) + 1.5$ and (4) $V_{606} - I_{814} < 1.5$.

Fig. 6 shows the fraction of galaxies recovered as a function of redshift for such a selection. Once again, the criteria appear to be very efficient at selecting relatively unreddened star-forming galaxies, this time in the redshift range $3.5 < z < 4.5$. Nevertheless, there is some danger of low-redshift contamination for the F450W dropouts. Again, most of the contaminants are either relatively old or red-

Table 1. Parameters grid of synthetic spectra.

Exponential Star Formation Timescales	$10^7, 10^8, 10^9, 5 \times 10^9, 10^{10}, 3 \times 10^{10} \text{ yr}$									
Constant Star Formation Durations	10^7 yr									
Metallicities	$Z_\odot, Z_\odot/100$									
A_B	0, 0.5, 1, 2, 3, 4, 5									
Extinction Laws	Galactic, LMC, SMC									
Redshifts	0.001	0.01	0.05	0.1	0.15	0.2	0.25	0.3	0.35	
	0.4	0.45	0.5	0.55	0.6	0.64	0.7	0.75	0.8	
	0.85	0.9	0.95	1.0	1.1	1.2	1.3	1.4	1.5	
	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	
	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	
	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2	
	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5.0	5.2	
	5.4	5.6	5.8	6.0	6.2	6.4	6.6	6.8	7.0	

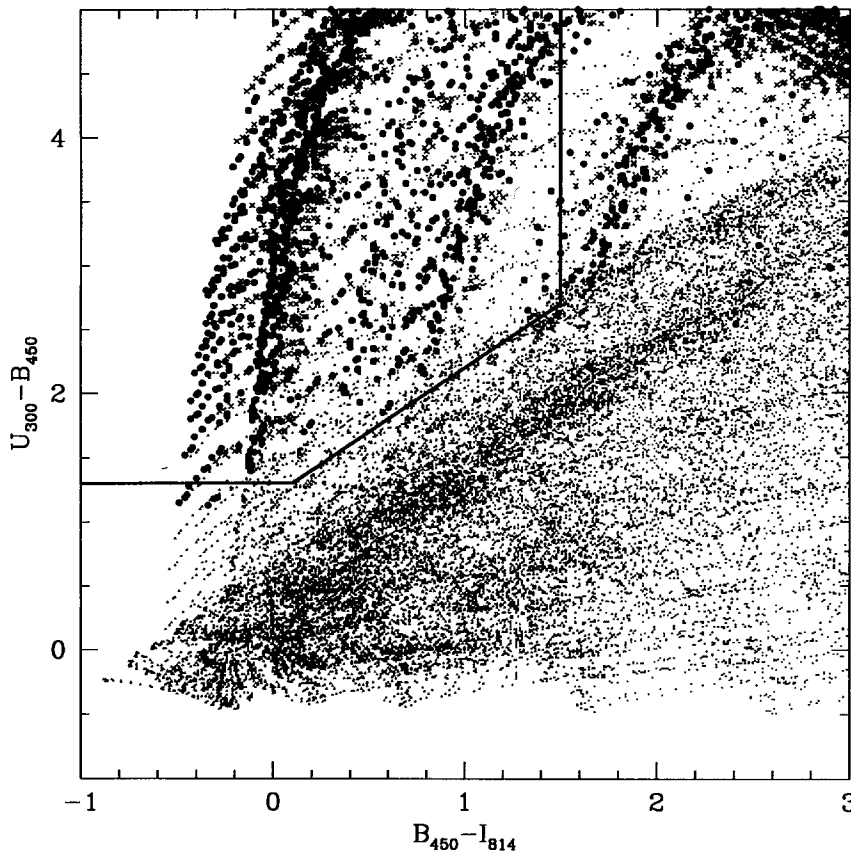


Figure 3. $U_{300} - B_{450}$ versus $B_{450} - I_{814}$ for model galaxies. A total of 103 879 synthetic spectra of galaxies representing a wide range of ages, star formation histories, metallicities, dust contents and redshifts were folded through the *HDF* bandpasses. The galaxies shown as small points are at redshifts of less than 2 or redshifts of greater than 3.5. Galaxies shown as solid circles are those in the redshift range $2 < z < 3.5$ with ages of less than 10^8 yr and extinctions $A_B < 1$. \times s are galaxies in the same redshift range that have ages greater than 10^8 yr or extinctions $A_B > 1$. Our colour selection criteria are shown as the large polygon. Galaxies within the polygon in the *HDF* observations are selected as likely candidates for $2 < z < 3.5$ objects. The selection criteria are $U_{300} - B_{450} > 1.3$, $U_{300} - B_{450} > B_{450} - I_{814} + 1.2$, and $B_{450} - I_{814} < 1.5$.

dened galaxies at slightly lower redshift. The dashed histogram in Fig. 6 shows the distribution of redshifts for the sample when galaxies are restricted to have either ages greater than 10^9 yr or $A_B > 2$. Again, the extent of the contamination in the real Universe depends on the unknown distribution of dust contents and ages at these redshifts.

4 HIGH-REDSHIFT GALAXIES IN THE HUBBLE DEEP FIELD

Using the colour selection criteria described above, we will build in this section a sample of galaxies at high redshifts selected from the Version 2 catalogue of the *HDF*, which is based on the second release of the reduced *HDF* images. Details of the data reduction, image combination, source detection and photometry are given by Williams et al. (1996).

Figs 7(a) and 8(a) show colour-colour plots of the catalogue data with our selection region drawn in as dashed lines. The catalogue is based on the three WF chips only, and covers an area of 4.65 arcmin^2 . The source detection was carried out on the exposure-weighted sum of the F606W and F814W images, and the threshold was set to 4σ . In all cases, isophotal magnitudes and colours were used for

photometry, with identical apertures (defined from a sum of the F606W and F814W images) applied to the images in all bandpasses. It is important to note that the FOCAS isophotal magnitudes are systematic *underestimates* of the true brightness of the galaxies. The magnitude error is difficult to quantify precisely as it depends on the surface brightness profiles of the galaxies in the image. Experiments on simulated data suggest that total magnitudes are typically 0.5 mag brighter than FOCAS isophotal magnitudes (Ferguson et al., in preparation). We have ignored this offset in our analysis, but note that it could increase our inferred luminosity densities and metal production rates by roughly a factor of 1.6. The catalogue was truncated at magnitude limits sufficiently bright that Lyman breaks of the expected amplitude could be measured reliably. For the *UBI* selection, we considered only objects with $B_{450} < 26.79$ and $V_{606} < 28.0$; for the *BVI* selection, the limiting threshold was set to $V_{606} < 27.67$. Galaxies undetected in F300W (F450W) – as defined by having signal-to-noise ratio < 1 inside the isophotal aperture – were assigned a 1σ lower limit to their $U_{300} - B_{450}$ ($B_{450} - V_{606}$) colours. In the figures, only objects with $I_{814} > 21$ are shown. For the *UBI* selection of F300W dropout objects, two bright stars (with $I_{814} < 21$) enter into the colour selection window. Steidel et al. (1996a)

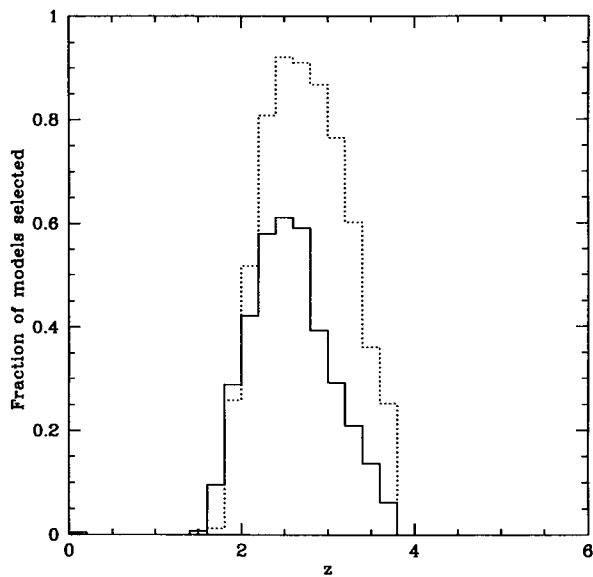


Figure 4. Selection efficiency for F300W dropouts. This figure provides a measure of colour selection in isolating galaxies with $2 < z < 3.5$. The solid histogram shows the fraction of models in each redshift interval ($\Delta z = 0.2$) that meet the colour selection criteria. The dotted histogram shows the fraction of models with ages less than 10^8 yr and extinctions $A_B < 2$ that meet the selection criteria. The colour selection criteria are extremely efficient at identifying relatively unobscured star-forming galaxies with $2 < z < 3.5$, and separating them from the chaff at other redshifts.

have shown that subdwarf stars may have similar colours to those of $z \sim 3$ galaxies, and indeed Steidel et al. (1996b) confirm that one of the two bright stars in the *HDF* within this colour selection window is indeed a foreground subdwarf star. None of the fainter F300W dropouts appear to be stellar.

The complex, sometimes multicomponent, morphologies of faint galaxies in deep *HST* images provide a complication for anyone cataloguing faint objects in images such as the *HDF*. Automated object detection routines may break up objects into several components if their light distribution has multiple peaks, and it is not always clear whether a multicomponent object should be considered as a 'single parent' entity or as being split into separate 'daughters'. We chose to apply our selection criteria to the complete catalogue of both parents and daughters, and then inspected all potential high-redshift candidates visually. In a few cases, we retained 'parents' as single objects (e.g., for the brightest F300W dropout, the elongated object known as C4-06 in the notation of Steidel et al. 1996b), while for others we chose the 'daughters' when the parent seemed to comprise distinctly separate objects. Although we will consider here only the total, summed light from all candidate Lyman break objects, the details of this splitting can be of some importance as the daughters may fall in or out of our sample.

Ultimately, of course, the ability of our colour criteria to select largely uncontaminated samples of star-forming galaxies at high redshifts must be confirmed by deep spec-

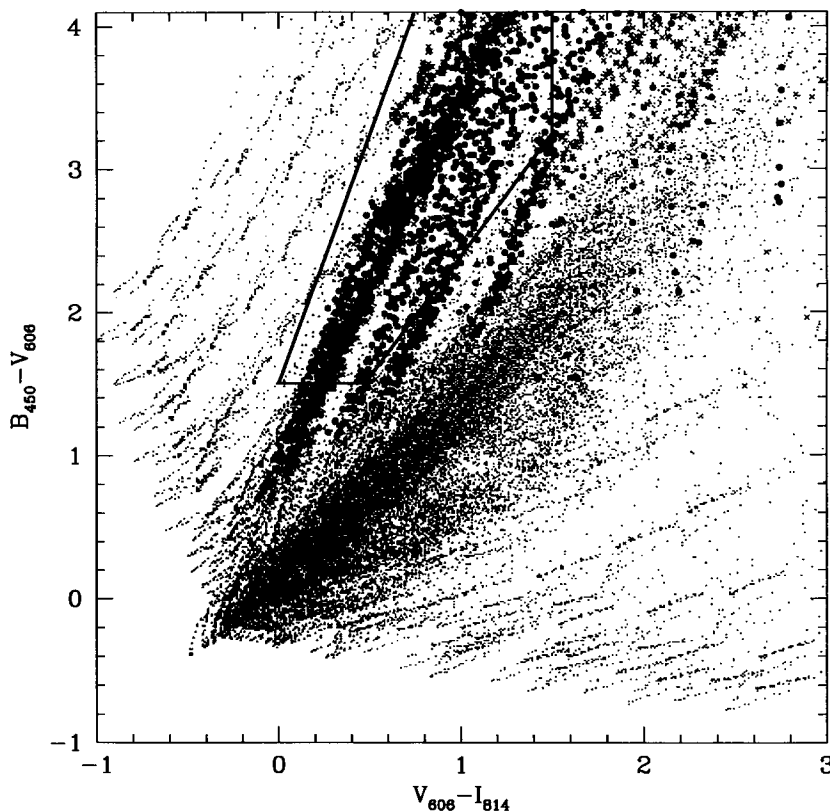


Figure 5. $B_{450} - V_{606}$ versus $V_{606} - I_{814}$ for model galaxies. The galaxies shown as small points are at redshifts of less than 3.5 or redshifts of greater than 4.5. Galaxies shown as solid circles are those in the redshift range $3.5 < z < 4.5$ with ages less than 10^8 yr and extinctions $A_B < 1$. \times s are galaxies in the same redshift range that have ages greater than 10^8 yr or extinctions $A_B > 1$. Our colour selection criteria are shown as the large polygon. Galaxies within the polygon in the *HDF* observations are selected as likely candidates for $3.5 < z < 4.5$ objects. The selection criteria are $B_{450} - V_{606} > 1.7(V_{606} - I_{814}) + 0.7$, $B_{450} - V_{606} > 1.5$, $B_{450} - V_{606} < 3.5(V_{606} - I_{814}) + 1.5$, and $V_{606} - I_{814} < 1.5$.

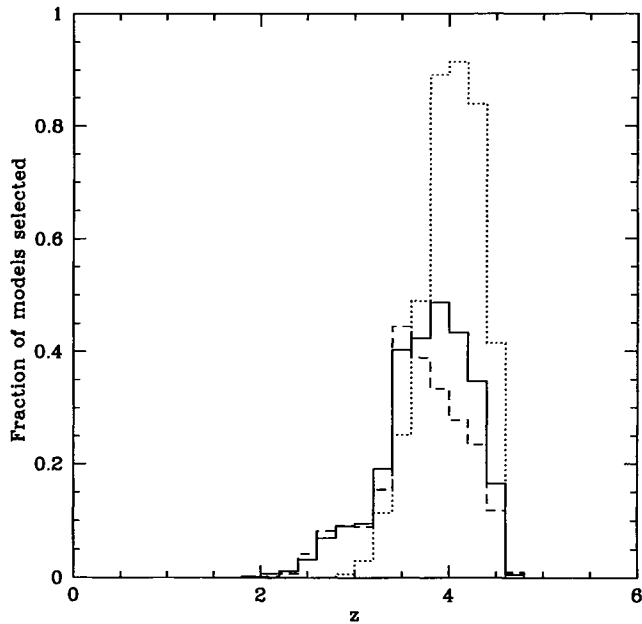


Figure 6. Selection efficiency for F450W dropouts. This figure provides a measure of colour selection in isolating galaxies with $3.5 < z < 4.5$. The solid histogram shows the fraction of models in each redshift interval ($\Delta z = 0.2$) that meet the colour selection criteria. The dotted histogram shows the fraction of models with ages less than 10^8 yr and extinctions $A_B < 2$ that meet the selection criteria. The primary source of contamination for the sample is galaxies at slightly lower redshifts with intrinsically red colours. The dashed line shows the fraction of the models with ages greater than 10^9 yr or $A_B > 2$ that meet the selection criteria. If such red objects at $2 < z < 3.5$ are very common, then our derived metal formation rate at higher redshifts may be an overestimate. However, we suspect that such old or dusty interlopers are much less common than blue star-forming galaxies at slightly higher redshift.

troscopy. In Figs 7(b) and 8(b) we plot the location in the colour–colour diagrams of the more than 60 galaxies in the *HDF* that have known Keck/LRIS spectroscopic redshifts (Steidel et al. 1996b; Cohen et al. 1996; Moustakas et al. 1996). While none of the low-redshift objects is found to contaminate our high-redshift selection regions, our *UBI* colour criteria are able to select four of the five objects spectroscopically confirmed by Steidel et al. (1996b) to be galaxies in the redshift range $2.591 < z < 3.226$. (Here, photometry from the Version 2 catalogues has been used, whereas Steidel et al. used Version 1 data.) Two out of the six known $z > 2$ objects in the *HDF* are *not* selected by our criteria. One ($z = 2.268$ galaxy from the Cohen et al. sample) only just misses being included – its $U - B$ colour is slightly bluer than allowed by our colour criteria. The second missed source (C4-09 from Steidel et al.) is a more puzzling case – this object is a small diamond-shaped configuration of four distinct subcomponents, each of which ‘disappears’ in the F300W bandpass. Steidel et al. considered it as a single object and measured a redshift of 3.23. We fail to identify it as a candidate because it appears as a formal detection (2.7σ) at F300W in the Version 2 catalogue, whereas Steidel et al. assigned only an upper limit to its U_{300} flux. This points to some uncertainty in our current

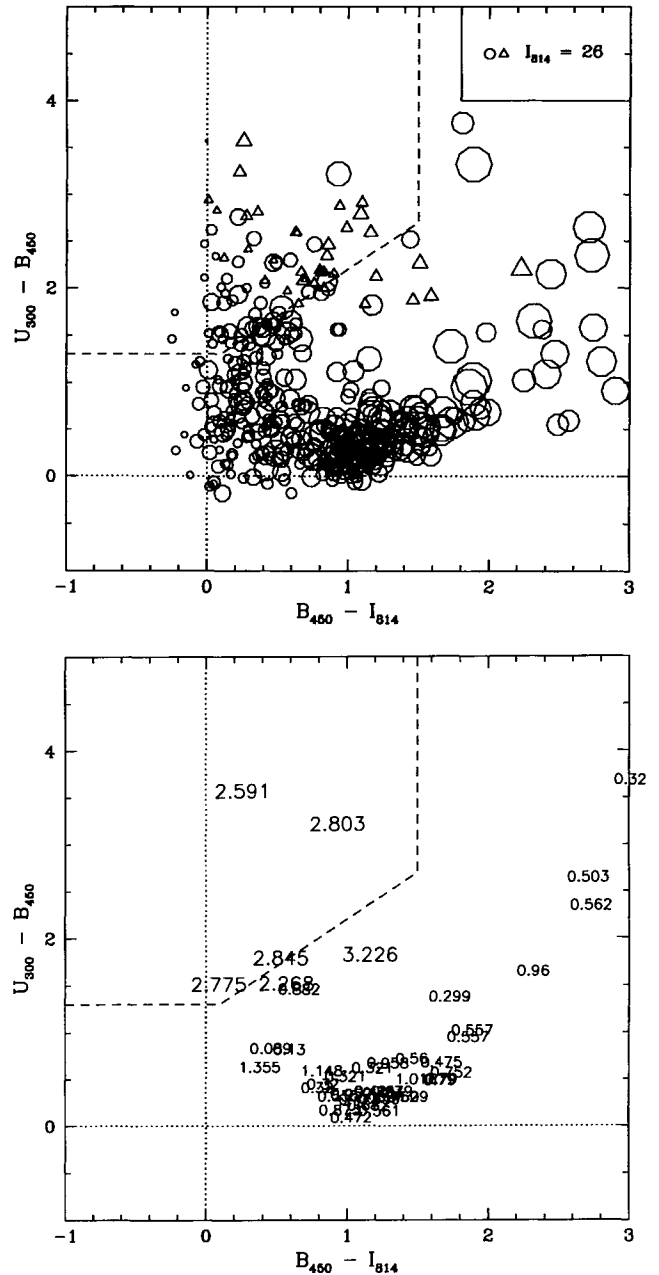


Figure 7. $U_{300} - B_{450}$ versus $B_{450} - I_{814}$ colour–colour plot of galaxies in the *HDF* satisfying the magnitude ranges given in the text. (a) Objects undetected in F300W (with signal-to-noise ratio < 1) are plotted as triangles at the 1σ lower limits to their $U_{300} - B_{450}$ colours. Symbol size scales inversely with the I_{814} magnitude of the object. The dashed lines outline the selection region within which we identify candidate $2 < z < 3.5$ objects. (b) Location in the colour–colour diagram of the more than 60 galaxies in the *HDF* that have known Keck/LRIS spectroscopic redshifts from Steidel et al. (1996b), Cohen et al. (1996) and Moustakas et al. (1996).

understanding of the noise properties of the F300W images, but we do not expect this to significantly impact the results presented here. In the Version 2 catalogue, the brightest of the four subcomponents of this small ‘quad’ is individually classified as a dropout above our magnitude limit and with the appropriate colours, and is included in the analysis presented here.

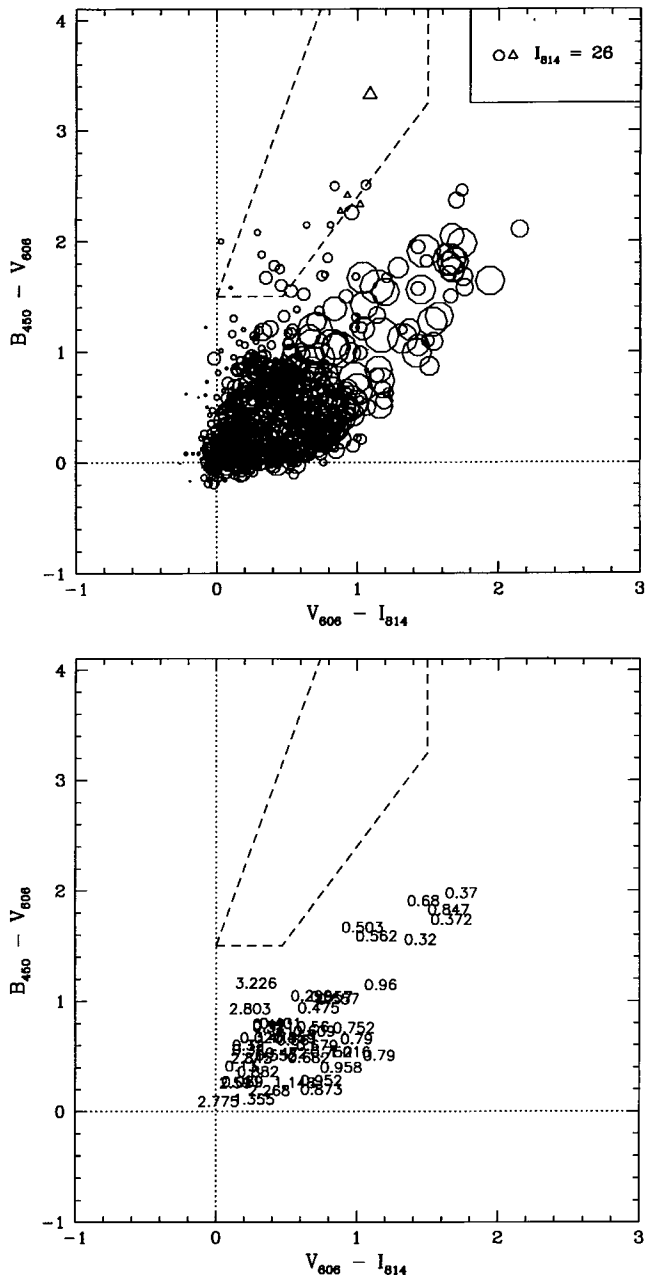


Figure 8. $B_{450} - V_{606}$ versus $V_{606} - I_{814}$ colour–colour plot of galaxies in the *HDF* satisfying magnitude ranges given in the text. (a) The symbol types and sizes are as described for Fig. 7(a). The selection area we define for candidate $3.5 < z < 4.5$ galaxies is outlined with dashed lines. (b) Same as Fig. 7(b).

4.1 F300W dropouts: limits to the luminosity density at $2 < z < 3.5$

We have identified 69 F300W dropouts in the *HDF* images that satisfy the criteria established for star-forming galaxies at $2 < z < 3.5$. Assuming this redshift interval has been uniformly probed, we derive a comoving galaxy number density of $4.2 \times 10^{-3} \text{ Mpc}^{-3}$ ($0.92 \times 10^{-3} \text{ Mpc}^{-3}$ for $q_0 = 0.05$) at $\langle z \rangle = 2.75$, about 10 times larger than the comoving space density of bright $L \geq L_*$ present-day galaxies (Loveday et al. 1992). The observed V_{606} magnitudes of our sample yield a specific (comoving) emissivity at 1620 \AA equal to

$$\rho_{1620} \approx 1.6 \times 10^{26} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3} \quad (8)$$

($9.0 \times 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}$ for $q_0 = 0.05$). The faintest F300W dropout has a magnitude of $V_{606} = 26.7$, corresponding, in the case of a flat-spectrum source at $\langle z \rangle = 2.75$, to a *B*-band luminosity of about $0.1L_*$, or a total star formation rate (Salpeter IMF) of $\sim 1 \text{ M}_\odot \text{ yr}^{-1}$. The brightest has $V_{606} = 23.6$, and is forming stars at a rate $\sim 20 \text{ M}_\odot \text{ yr}^{-1}$.

It is interesting to compare the comoving space density of the *HDF* F300W dropouts brighter than $V_{606} = 25$, $7.3 \times 10^{-4} \text{ Mpc}^{-3}$ at $\langle z \rangle = 2.75$, with that derived from the Steidel et al. (1996a) ground-based statistic, $3.6 \times 10^{-4} \text{ Mpc}^{-3}$ to $\mathcal{R} < 25$ at redshift $\langle z \rangle = 3.25$. Within the errors, the two estimates appear to be in good agreement with one another, especially after accounting for the fact that one probes to $\sim 0.3 \text{ mag}$ fainter in the galaxy luminosity function at the *HDF* average redshift.

4.2 F450W dropouts: limits to the luminosity density at $3.5 < z < 4.5$

In a similar manner, we have identified 14 F450W dropouts that satisfy the criteria established for star-forming galaxies at $3.5 < z < 4.5$. Their comoving number density at $\langle z \rangle = 4.0$ is $1.5 \times 10^{-3} \text{ Mpc}^{-3}$ ($2.4 \times 10^{-4} \text{ Mpc}^{-3}$ for $q_0 = 0.05$). From the observed I_{814} magnitudes, we derive a specific (comoving) emissivity at 1630 \AA of

$$\rho_{1630} \approx 5.0 \times 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3} \quad (9)$$

($2.8 \times 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}$ for $q_0 = 0.05$). The faintest F450W dropout has a magnitude of $I_{814} = 27.5$, corresponding, in the case of a flat-spectrum source at $\langle z \rangle = 4$, again to a *B*-band luminosity of about $0.1L_*$, while the brightest has $I_{814} = 25$. Our samples of U_{300} and B_{450} dropouts therefore reach comparable depths. *We stress that, contrary to the case at $2 < z < 3.5$, we have as yet no spectroscopic confirmation of the efficiency of our colour-selection criteria at $3.5 < z < 4.5$.*

The source catalogues of the U_{300} and B_{450} dropouts are presented in Tables 2 and 3. For each galaxy we report the FOCAS catalogue entry number from Williams et al. (1996) (ID), the right ascension and declination (α, δ), and the *AB* isophotal magnitudes in the four *HDF* passbands.⁴ The UV dropouts 2-449.0, 3-550.0, 4-555.1 and 4-676.0 have been spectroscopically identified by Steidel et al. (1996b) as galaxies at $z = 2.845, 2.775, 2.803$ and 2.591 , respectively.

5 COSMIC STAR FORMATION HISTORY

The results of the Canada–France Redshift Survey (CFRS: Lilly et al. 1995) over the redshift range $0 < z < 1$ and the spectroscopic confirmation by Steidel et al. (1996a, b) of the existence of a substantial population of luminous, star-forming galaxies at $2.5 < z < 3.5$, together with our statistical constraints on the redshift distribution of faint galaxies in

⁴The use of a more conservative criterion that assigns a 2σ lower limit to the $U_{300} - B_{450}$ colours of galaxies undetected in the F300W bandpass would decrease the number of ultraviolet dropouts to 47, thereby decreasing the integrated emissivity given in equation (8) by a factor of 1.3. The same 2σ colour criterion applied to galaxies undetected in F450W decreases the number of blue dropouts to only nine, resulting in an emissivity that is a factor of 1.4 lower than that given in equation (9).

Table 2. *HDF* U_{300} dropouts.

ID	α (h:m:s)	δ (°:′:″)	U_{300}	B_{450}	V_{606}	I_{814}
2-82.1	12:36:44.066	62:14:09.92	26.62	24.77	24.72	24.74
2-122.0	12:36:47.766	62:13:18.96	>28.88	26.28	25.75	25.65
2-213.0	12:36:46.768	62:13:54.75	>28.64	26.67	26.21	26.10
2-239.0	12:36:45.886	62:14:12.09	26.45	24.86	24.58	24.50
2-373.0	12:36:50.302	62:13:29.73	27.02	25.45	25.27	25.13
2-392.0	12:36:49.813	62:13:43.02	28.55	26.54	26.44	26.44
2-449.0	12:36:48.336	62:14:16.63	25.74	23.95	23.71	23.42
2-456.12	12:36:49.929	62:13:49.38	>29.36	26.77	26.30	26.13
2-456.22	12:36:50.027	62:13:51.99	26.81	25.27	25.19	25.11
2-525.0	12:36:50.123	62:14:01.03	27.44	25.17	24.88	24.70
2-547.0	12:36:51.361	62:13:44.66	27.94	26.07	25.93	25.89
2-565.1	12:36:51.189	62:13:48.78	>29.54	26.66	25.99	25.72
2-637.0	12:36:52.759	62:13:39.08	>28.82	26.23	25.31	25.07
2-643.0	12:36:53.424	62:13:29.52	>28.50	25.71	24.89	24.62
2-726.0	12:36:53.124	62:13:46.25	>28.61	26.44	25.84	25.63
2-741.0	12:36:52.150	62:14:05.75	28.69	26.64	26.28	26.23
2-746.0	12:36:53.557	62:13:44.02	>28.80	26.74	26.13	25.98
2-751.0	12:36:54.204	62:13:35.83	27.70	26.24	26.43	26.49
2-822.0	12:36:54.001	62:13:51.61	28.31	26.57	26.71	26.80
2-824.0	12:36:54.628	62:13:41.36	27.25	25.41	25.27	25.29
2-889.0	12:36:52.240	62:14:30.52	>28.53	26.36	25.84	25.69
2-890.0	12:36:52.075	62:14:33.84	28.30	26.02	25.94	25.80
2-903.0	12:36:55.077	62:13:47.00	26.72	24.79	24.62	24.57
2-916.0	12:36:55.184	62:13:48.07	27.59	25.86	25.51	25.35
2-949.0	12:36:54.599	62:14:03.67	27.80	25.96	25.66	25.58
2-999.0	12:36:56.634	62:13:39.78	>28.48	26.13	25.83	25.28
3-41.0	12:36:53.603	62:13:17.92	>29.03	26.09	26.06	26.08
3-83.0	12:36:56.798	62:13:24.10	27.62	25.90	25.69	25.56
3-126.0	12:36:52.833	62:13:08.51	27.47	26.05	25.87	25.88
3-221.2	12:36:57.867	62:13:15.28	>29.45	26.54	25.78	25.44
3-286.0	12:36:49.611	62:12:44.66	28.46	26.52	26.42	26.39
3-321.2	12:36:50.449	62:12:44.78	27.15	25.65	25.53	25.41
3-335.0	12:36:53.355	62:12:52.30	>28.84	26.69	26.15	25.79
3-504.0	12:36:57.622	62:12:49.19	27.72	26.19	26.17	26.10
3-510.0	12:36:51.952	62:12:31.47	>28.61	26.53	26.22	26.12
3-550.0	12:36:51.335	62:12:27.51	26.45	24.94	24.87	24.85
3-633.1	12:36:51.604	62:12:22.47	28.08	26.46	26.18	26.04
3-677.0	12:36:51.620	62:12:17.31	28.37	25.90	25.55	25.14
3-736.0	12:36:55.636	62:12:23.64	27.89	26.37	26.38	26.36
3-748.0	12:36:59.978	62:12:35.95	>28.84	26.54	26.16	26.07
3-813.0	12:36:59.241	62:12:27.29	>28.78	26.58	25.86	25.78
3-902.0	12:36:51.787	62:11:57.81	>28.51	26.19	26.01	26.07
3-916.0	12:36:58.297	62:12:16.58	28.24	25.94	25.60	25.35
4-83.0	12:36:50.383	62:12:05.06	>28.87	26.77	26.21	26.07
4-85.2	12:36:49.682	62:12:19.64	28.08	25.55	25.31	25.22
4-96.0	12:36:47.910	62:12:43.12	28.76	26.65	26.65	26.67
4-194.0	12:36:49.796	62:11:55.42	>28.80	26.62	25.98	25.79
4-252.0	12:36:45.589	62:12:54.68	27.93	26.47	26.40	26.36
4-289.0	12:36:46.947	62:12:26.08	>28.69	25.45	25.20	25.22
4-316.0	12:36:45.086	62:12:50.81	26.01	24.42	24.28	24.13
4-317.0	12:36:48.750	62:11:47.65	>29.18	26.35	26.21	26.28
4-363.0	12:36:48.302	62:11:45.85	>28.37	25.91	25.22	25.05
4-382.1	12:36:46.951	62:12:05.34	27.04	24.97	24.47	24.12
4-389.0	12:36:45.626	62:12:24.90	>28.93	26.52	26.28	26.23
4-488.0	12:36:46.525	62:11:45.57	28.23	26.13	26.04	25.99
4-491.0	12:36:43.253	62:12:38.86	27.84	25.08	24.89	24.86
4-497.0	12:36:45.728	62:11:57.31	>28.93	26.11	25.83	25.75
4-555.1	12:36:45.409	62:11:53.17	27.48	24.26	23.57	23.33
4-576.0	12:36:44.025	62:12:09.61	28.02	26.06	25.51	25.34
4-588.0	12:36:41.879	62:12:43.66	>28.07	25.99	25.43	25.31
4-590.0	12:36:43.310	62:12:18.27	28.56	26.29	26.02	25.80
4-599.0	12:36:43.193	62:12:19.18	28.57	26.57	26.28	26.29
4-639.1	12:36:41.712	62:12:38.75	>28.48	24.91	24.82	24.65
4-660.0	12:36:42.950	62:12:11.53	28.60	25.98	25.93	25.95
4-676.0	12:36:41.708	62:12:31.04	>28.47	25.70	25.47	25.42
4-681.0	12:36:44.600	62:11:39.44	29.02	26.55	26.50	26.57
4-825.0	12:36:42.325	62:11:50.35	27.75	26.34	26.38	26.30
4-926.2	12:36:39.562	62:12:13.83	>29.06	26.41	25.57	25.42
4-936.0	12:36:40.801	62:11:50.60	29.07	26.73	26.67	26.67

Table 3. *HDF* B_{450} dropouts.

ID	α (h:m:s)	δ (°:':")	U_{300}	B_{450}	V_{606}	I_{814}
2-493.0	12:36:50.641	62:13:49.36	>29.19	29.15	27.57	27.47
2-977.0	12:36:55.771	62:13:50.92	>29.01	28.45	26.70	26.25
3-195.0	12:36:48.577	62:12:48.51	28.05	28.17	26.39	25.98
3-223.0	12:36:52.786	62:12:58.95	29.06	29.59	27.44	26.80
3-231.1	12:36:51.914	62:12:55.69	>29.20	>29.95	27.53	26.60
3-512.0	12:36:56.120	62:12:44.68	>28.50	27.58	25.91	25.56
3-534.2	12:36:59.245	62:12:54.38	>29.60	29.76	27.61	26.80
3-675.0	12:36:57.174	62:12:34.30	>28.67	27.76	26.16	25.70
3-705.0	12:36:51.690	62:12:15.09	>29.05	28.86	26.98	26.66
3-783.0	12:36:58.954	62:12:29.02	28.87	29.62	27.12	26.28
4-277.0	12:36:48.943	62:11:52.85	>29.19	29.75	27.24	26.18
4-280.0	12:36:46.672	62:12:30.12	29.03	29.25	27.17	26.88
4-439.0	12:36:43.842	62:12:41.60	>28.63	>29.39	26.06	24.97
4-702.0	12:36:43.629	62:11:50.79	28.51	>29.81	27.53	26.65

the *HDF*, as derived above for $2 < z < 4.5$, have considerable implications for our understanding of the global history of star and structure formation in the Universe. Here, we review some of the consequences of these observations, focusing on what can be learned about galaxy evolution at early (and late) epochs from integrated quantities over the entire population, rather than from a detailed study of individual objects.

5.1 The metal production density of the Universe

The UV continuum emission from a galaxy with significant ongoing star formation is totally dominated by short-lived massive stars, and is therefore nearly independent of the galaxy history. Moreover, the (rest-frame) radiation flux below 3000 Å is a very good measurement of the instantaneous ejection rate of heavy elements ($Z \geq 6$), since both are directly related to the number of massive stars (Cowie 1988; Songaila, Cowie & Lilly 1990; Madau & Shull 1996): the same stars with $m > 10 M_{\odot}$ that manufacture and return most of the metals to the ISM also dominate the UV light. The supernova event from a star of $25 M_{\odot}$ implies the injection of about $4.5 M_{\odot}$ of metals (Woosley & Weaver 1995). At the end of the C-burning phase, $\sim 17 M_{\odot}$ have been converted into helium and carbon (Maeder 1992), with a mass fraction released as radiation of 0.007. For each $1 M_{\odot}$ of metals ejected, to first approximation we then expect $(17 \times 0.007/4.5) = 0.025 M_{\odot} c^2$ of energy to be radiated away.

What we are interested in here is the universal rate of ejection of newly synthesized material per unit comoving volume. In the approximation of instantaneous recycling, the metal ejection rate (MER) per unit volume can be written as (cf. Tinsley 1980)

$$\dot{\rho}_Z = \psi \int m p_{\text{zm}} \phi(m) dm, \quad (10)$$

where ψ is the star formation rate (SFR) density, $\phi(m)$ is the IMF [normalized through the relation $\int m \phi(m) dm = 1$], and p_{zm} is the stellar yield, i.e., the mass fraction of a star of mass m that is converted to metals and ejected. The dot denotes differentiation with respect to cosmic time. At short wavelengths, the luminosity density radiated per unit frequency during the main-sequence phase is related to ψ by

$$\rho_{\nu} = 0.007 c^2 \psi \int m f_{\text{He}}(m) f_{\nu}(m) \phi(m) dm, \quad (11)$$

where $f_{\text{He}}(m)$ is the mass fraction of hydrogen burned into helium, and $f_{\nu}(m)$ is the normalized spectrum of stars of mass m on the main sequence. The detailed conversion from UV luminosity to MER, including all evolutionary stages, can be obtained from spectral synthesis and metal-yield calculations. For simplicity, we will ignore here the contributions of planetary nebulae (Renzini & Voli 1981), Type Ia supernovae (Thielemann, Nomoto & Yokoi 1986) and stellar winds (Maeder 1992) to the chemical yields, and focus on the nucleosynthetic enrichment by supernova explosions from massive stars. We use the evolutionary models of Bruzual & Charlot (1993) and the Type II stellar yields tabulated by Woosley & Weaver (1995) (see also Sutherland & Shull, in preparation). For a Salpeter IMF including stars in the $0.1 < M < 125 M_{\odot}$ mass range, a constant SFR, a galaxy age in the internal 0.1–1 Gyr, and solar metallicity, we derive

$$\rho_{1500} = 4.4 \pm 0.2 \times 10^{29} \dot{\rho}_Z \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3} \quad (12)$$

at 1500 Å, and

$$\rho_{2800} = 2.8 \pm 0.3 \times 10^{29} \dot{\rho}_Z \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3} \quad (13)$$

at 2800 Å, where $\dot{\rho}_Z$ is the MER in $M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$. The continuum spectrum is fairly flat and is dominated by early-type stars. We shall use the relations given above in the subsequent discussion, while noting that the conversion efficiency is fairly insensitive to the assumed IMF (as long as the stellar population extends as a power law to massive stars, 50–100 M_{\odot}), since the increased metal yield from high-mass stars is compensated for by a similar increase in the production of UV photons. The advantage, then, of deriving from the observed UV luminosity density a rate of metal ejection rather than an SFR, is that the latter is instead a sensitive function of the IMF slope. To be quantitative, while for a Salpeter IMF the mean yield of returned metals is

$$\int m p_{\text{zm}} \phi(m) dm = 2.4 \text{ per cent}, \quad (14)$$

for a Scalo (1986) IMF – less rich in massive stars – in the same mass range this factor is about 3.3 times lower. Hence

large errors in the relative rates of star formation at different epochs may occur if the IMF varies with cosmic time. Because of these considerations, unless otherwise stated we will only quote MERs in the following. Note, however, that the real uncertainties in the UV-to-metal conversion factors due to age, IMF, metallicity and population synthesis model well exceed the errors quoted above.

To relate the amount of heavy elements observed today in various stellar populations and in the gas phase to the UV luminosity of distant, star-forming galaxies, we may use the conservation of metals, which implies that the sum of the heavy elements stored in stars, $Z_*\rho_*$, and in the gas, $Z_g\rho_g$, is equal to the mass of all metals ever ejected, i.e., to the integral of equation (10) over cosmic time. An estimate of the baryonic mass in galaxies can be obtained by multiplying the observed luminosity density of the local Universe by a mass-to-light ratio. Since the gaseous content of nearby galaxies is observed to be negligible compared with the stellar content (e.g., Rao & Briggs 1993), the cosmological mass density of heavy elements at the present epoch is given by

$$\rho_Z(0) \approx Z_*\rho_*(0) = Z_*\rho_B(0) \left(\frac{M}{L_B} \right), \quad (15)$$

where $\rho_B(0)$ is the local blue light density of field galaxies, and M/L_B is the mass-to-blue light ratio of visible matter. There are several recent determinations of the B -band luminosity density from large redshift surveys. The values obtained for $\log \rho_B(0)$ in units of $L_\odot \text{ Mpc}^{-3}$ are 7.98 (Efsthathiou, Ellis & Peterson 1988), 7.83 (Loveday et al. 1992), 8.0 (Marzke, Huchra & Geller 1994), 7.93 (da Costa et al. 1994), and 8.0 (Ellis et al. 1996). A simple average of all these determinations gives the adopted value

$$\rho_B(0) = 9.0 \pm 1.4 \times 10^7 L_\odot \text{ Mpc}^{-3}. \quad (16)$$

The mass-to-light ratios for the visible parts of galaxies can be estimated from stellar population modelling. The results (in solar units) are in the range $2 < M/L_B < 6$, the smaller value referring to a typical Population I system such as the solar neighbourhood (e.g., Kuijken & Gilmore 1989), the larger value to the old stellar populations of elliptical galaxies (e.g., van der Marel 1991). Since about 30 per cent of the total blue luminosity density is in ellipticals (Efsthathiou et al. 1988), we may adopt the luminosity-weighted mean value of $\langle M/L_B \rangle = 3$ to derive

$$\rho_Z(0) \approx 5.4 \pm 0.8 \times 10^6 \left(\frac{Z_*}{Z_\odot} \right) M_\odot \text{ Mpc}^{-3} \quad (17)$$

(cf. Cowie 1988). While representative stellar metallicities in nearby luminous spirals and ellipticals are approximately solar, $Z_* \sim Z_\odot = 0.02$, irregular, blue compact and dwarf spheroidal galaxies are known to be metal poor, $Z_* \gtrsim 0.1 Z_\odot$ (e.g., Pagel & Edmunds 1981).

The real uncertainty on the metal mass density is difficult to estimate, but is unlikely to exceed a factor of 1.5. Although a baryonic mass several times larger than the luminous mass may be present in the Galactic halo, metal-rich halo material would be mixed into and would over-enrich the disc. Hence, if a substantial amount of metals is missing from our census, it is most likely hidden in low

surface brightness galaxies (Ferguson & McGaugh 1995), or in intergalactic and intracluster gas.

It is useful at this stage to define a fiducial metal ejection density,

$$\dot{\Sigma}_Z = \rho_Z(0) t_H(0)^{-1} \approx 4.2 \times 10^{-4} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}, \quad (18)$$

given by the present-day mass density in heavy elements divided by the current age of the Universe. If $\dot{\rho}_Z$ observed at a given redshift z is much less than $\dot{\Sigma}_Z$, and a large fraction of the luminous baryons observed today were already locked into galaxies at this epoch, then either galaxies have already exhausted their reservoirs of cold gas or there must be a mechanism that prevents the gas within virialized dark matter haloes from radiatively cooling and turning into stars. By contrast, an MER much greater than the fiducial value implies that the conversion of gas into stars can be extremely efficient at times. From a comparison between the observed $\dot{\rho}_Z$ and $\dot{\Sigma}_Z$ we may then be able to distinguish between a more or less uniform (with cosmic time) SFR and a discontinuous one, consisting of a series of bursts of suitable duty cycle.

According to Gallego et al. (1995), the $H\alpha$ luminosity density of the local Universe is $\rho_{H\alpha}(0) = 1.3 \pm 0.6 \times 10^{39} \text{ erg s}^{-1} \text{ Mpc}^{-3}$. This value implies⁵ an MER at the present epoch of

$$\dot{\rho}_Z(0) \approx 1.1 \pm 0.5 \times 10^{-4} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}. \quad (19)$$

Equations (18) and (19) suggest that the present rate of production of heavy elements is too low to yield the observed element abundances in the Hubble time, and that either star-forming galaxies were much more numerous in the past or individual galaxies must, on average, have passed through a significantly brighter phase.

From the CFRS faint galaxy survey (Lilly et al. 1995), we now know that the MER per unit mass was in fact considerably larger in the past. The comoving metal ejection density at $0 < z < 1$ corresponding to the observed specific luminosity density at 2800 Å (the 'LF-estimated' value of Lilly et al. 1996) is

$$\dot{\rho}_Z(z) \approx 1.5 \pm 0.6 \times 10^{-3} \left(\frac{1+z}{2} \right)^{3.9} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}, \quad (20)$$

about 15 times higher at $z \sim 1$ than the current value. This strong evolution is associated with galaxies bluer than typical Sbc's. The luminosity function of redder galaxies shows little change back to $z \sim 1$.

The sample of Lyman break star-forming galaxies identified by Steidel et al. (1996a) has a comoving density of $\approx 3.6 \times 10^{-4} \text{ Mpc}^{-3}$ at $\langle z \rangle = 3.25$, and an average continuum specific luminosity at 1500 Å of $10^{41} \text{ erg s}^{-1} \text{ Å}^{-1}$. This gives a comoving volume emissivity of $2.7 \times 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3}$, hence an MER density of

⁵In case-B recombination theory, the $H\alpha$ luminosity density can be related to the emission rate of ionizing photons per unit cosmic volume, \dot{n}_{ion} , according to $\rho_{H\alpha} \approx 0.45 h \nu_{H\alpha} \dot{n}_{\text{ion}}$ (Osterbrock 1989). Population synthesis galaxy spectra (Bruzual & Charlot 1993) with constant SFR yield the following approximate relation between ρ_{1500} and \dot{n}_{ion} : $\dot{n}_{\text{ion}} \approx 0.14 \rho_{1500}/h$, nearly independently of age in the interval 0.1–1 Gyr.

$$\dot{\rho}_Z(3.25) \approx 6.2 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}, \quad (21)$$

comparable with the local value but more than 20 times lower than the $z=1$ one.⁶

Finally, our analysis of the *HDF* images yields, from equations (8) and (9),

$$\dot{\rho}_Z(2.75) \approx 3.6 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}, \quad (22)$$

and

$$\dot{\rho}_Z(4) \approx 1.1 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}. \quad (23)$$

Note that the MER density at $\langle z \rangle = 2.75$ is more than a factor of 5 larger than the Steidel et al. (1996a) ground-based value at $\langle z \rangle = 3.25$, largely because the *HDF* deep images probe about 1.7 mag deeper into the rest-frame luminosity function at these redshifts. Still, the derived luminosity density is significantly smaller than the rate at $z \approx 1$. It is conceivable that our list of candidates in the *HDF* may be sampling a significant fraction of the galaxy luminosity function at these redshifts, and that the contribution to the luminosity density from galaxies below our magnitude threshold is small. Strictly speaking, however, the MERs derived above from the *HDF* data (and the emissivities given in equations 8 and 9) should be interpreted as lower limits to the real values, as they only include the fraction arising in the most actively star-forming, young and nearly dust-free objects. The same considerations also apply to the sample identified by Steidel et al. (1996a). We point out that large numbers of faint galaxies at high redshifts are quite plausible in cold dark matter like cosmologies, because of the high space density of low-mass dark matter haloes predicted in any hierarchical theory of galaxy formation (e.g., White & Frenk 1991).

The derived star and element formation history of the Universe is depicted in Fig. 9. Although the star formation densities beyond $z=2$ are only lower limits, together with the Gallego et al. and Lilly et al. values, they seem consistent with the existence of a peak in the cosmic metal production rate in the redshift range $1 \lesssim z \lesssim 2$, as predicted by models of the chemical evolution of the damped Ly α absorption systems (Pei & Fall 1995).

5.2 Clues to galaxy formation and evolution

We may at this stage try to establish a cosmic timetable for the production of heavy elements in relatively bright galaxies, keeping in mind the inherent uncertainties associated with the estimates given above. In an Einstein–de Sitter universe, the total mass density processed into metals over the redshift range $0 < z < z_c \approx 1$, is, integrating equation (20) over cosmic time,

$$\Delta \rho_Z(0) = (8.2 \pm 2.6 \times 10^5 \text{ M}_\odot \text{ Mpc}^{-3}) [(1 + z_c)^{2.4} - 1] \\ = 3.5 \pm 1.1 \times 10^6 \text{ M}_\odot \text{ Mpc}^{-3}. \quad (24)$$

(Contrary to the measured number densities of objects and rates of star formation, the metal mass density does not depend on the assumed cosmological model.) If we define two characteristic epochs of star and element formation in

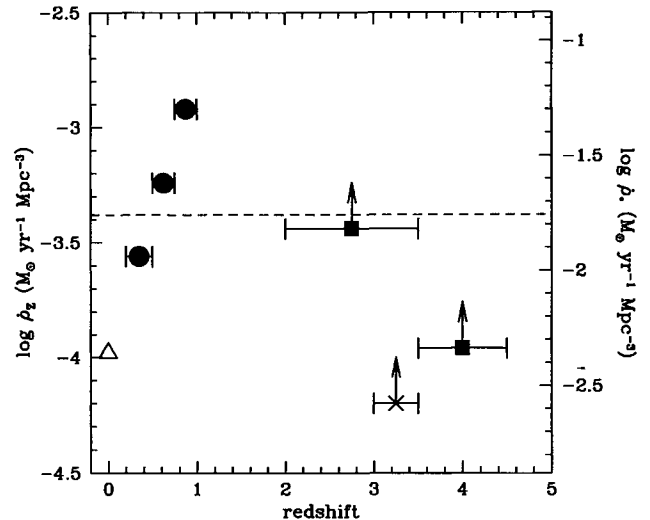


Figure 9. Element and star formation history of the Universe. The data points from various surveys provide a measurement or a lower limit to the Universal metal ejection density, $\dot{\rho}_Z$, as a function of redshift. For a Salpeter IMF, to translate $\dot{\rho}_Z$ into a total star formation density, $\dot{\rho}_*$, a factor of 42 should be applied. Triangle: Gallego et al. (1995). Filled dots: Lilly et al. (1996). Diagonal cross: lower limit from Steidel et al. (1996a). Filled squares: lower limits from the *HDF* images. The dashed line depicts the fiducial rate, $\dot{\Sigma}_Z$, given by the mass density of metals observed today divided by the present age of the Universe (see text for details). A flat cosmology with $q_0=0.5$ and $H_0=50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ has been assumed.

galaxies, z_* and z_Z , as the redshifts by which half of the current stellar and metal content of galaxies was formed, then a straightforward comparison between equations (17) and (24), together with the fact that most of the stars in the inner luminous parts of galaxies are metal-rich, implies that $z_* \lesssim z_Z \approx 1$, or in other words that a significant fraction of the current metal content of galaxies was formed relatively late, on a time-scale of about 8 Gyr. This is comparable with the decay time of star formation, from 5 to 9 Gyr, required to reproduce the present-day colours of late-type spirals (e.g., Bruzual & Charlot 1993), and suggests the possibility that we may be observing in the redshift range $z=0-1$ the conversion into stars of gaseous galactic discs. Pure H I discs may be assembled at some higher redshift, and disc gas continuously replenished as a result of ongoing infall from the surrounding hot halo. The case for a ‘disc epoch’ at $z \sim 1$ is strengthened by the observations that galaxies of different luminosities and morphological types evolve very differently. A common conclusion of several recent deep redshift surveys (e.g., Glazebrook et al. 1995, Lilly et al. 1995, Ellis et al. 1996) is that late-type, gas-rich systems show substantial evolution in number and/or luminosity from the present to $z \sim 1$, and that a large fraction of the observed evolution is associated with an increase in the mean surface brightness of luminous discs (Schade et al. 1995). By contrast, the ellipticals and early-type spirals have been remarkably quiescent over the same redshift interval.

From stellar population studies we also know that about half of the present-day stars – and hence metals – are contained in spheroidal systems, i.e., elliptical galaxies and spiral galaxy bulges, and that these formed early and rapidly. The major arguments come from studies of Galactic

⁶Note that the star formation density at $z=0$ quoted by Gallego et al. (1995) is derived assuming a Scalo IMF, while Steidel et al. (1996a) adopt a Salpeter IMF in their paper.

bulge colour–magnitude diagrams (Ortolani et al. 1995), which indicate ages as old as globular clusters, and from studies of the chemical abundances in cluster ellipticals and cluster X-ray gas, whose high α -element ratios suggest that both the stars and the intracluster gas must have been enriched on time-scales of the order of 1 Gyr or less (Renzini et al. 1993). If these arguments are correct (and they are by no means undisputed), then bulges and ellipticals must have experienced a bright starburst phase at high redshift. Where are these protospheroids?

There are a few pieces of circumstantial evidence supporting the interpretation that the Lyman break galaxies identified at $z > 2.5$ from ground-based images may represent the progenitors of present-day luminous galaxies while forming their spheroidal stellar component. From the strength of their interstellar UV absorption lines, and within the assumption that their velocity field is dominated by gravity, Steidel et al. (1996a) have shown that galaxies at $z \sim 3$ have masses comparable to that of present-day L_* galaxies. Smaller masses would result if interstellar shocks, local to the star-forming regions, contribute significantly to the velocity field. While the *HST* images of these galaxies show the presence of compact (half-light radii of 0.2–0.3 arcsec) cores (Giavalisco et al. 1996), from the deeper *HDF* data it seems that the F300W dropouts may be better described as asymmetric or irregular objects (Abraham et al. 1996; van den Bergh et al. 1996).

The observations described above may confirm the rationale that galaxies form stars from the inside out, i.e., that spheroidal systems have assembled rather early, far beyond the disc epoch at $z \sim 1$. At the star formation density levels inferred from the *HDF* images at $\langle z \rangle = 2.75$ (see equation 22) about 15 per cent of the observed mass density of metals at $z=0$ would have been formed during the ‘spheroid epoch’ at $z \gtrsim 2$. This fraction could increase if the star formation is shrouded in dust or takes place in galaxies small enough individually to fall below the *HDF* source detection limit. On the other hand, since the metals we observe being formed are a substantial fraction of the entire metal content of galaxies, *it appears that star formation regions remain largely unobscured by dust throughout much of galaxy formation.*

With the data presented here, two arguments that have implications for models of galaxy formation can be made more quantitative.

(i) From Efstathiou et al. (1988), the space density of bright ellipticals today is $n(>L_*) = 2.4 \times 10^{-4} \text{ Mpc}^{-3}$. If a significant fraction of their stellar population formed in a single burst of duration 1 Gyr early in the history of the Universe, a comparable number density of objects should be observed at high redshift while forming stars at rates in excess of $50\text{--}100 \text{ M}_\odot \text{ yr}^{-1}$. We find that none of the *HDF* F300W dropouts spectroscopically confirmed by Steidel et al. (1996b) has an SFR in excess of $20 \text{ M}_\odot \text{ yr}^{-1}$ (Salpeter IMF). Assuming a probed redshift interval between 2 and 3.5, we can set an upper limit to the comoving density of very highly star-forming galaxies at $\langle z \rangle = 2.75$, $n(>20 \text{ M}_\odot \text{ yr}^{-1}) < 6 \times 10^{-5} \text{ Mpc}^{-3}$. Hence there appears to be a deficit of very bright objects relative to the expectations of the standard early-and-rapidly-forming picture for spheroidal systems.

(ii) In hierarchical models of galaxy formation, small objects form first and merge together to make larger ones. While much of the activity associated with star formation and galaxy merging occurs at relatively low redshifts (White & Frenk 1991), there is no period when bulges and ellipticals form rapidly as single units and are very bright: rather, galaxies become progressively less luminous, more numerous, and more compact at earlier epochs. A common prediction of hierarchical models appears to be the steepening with lookback time of the luminosity function due to the large increase in the abundance of objects forming stars at modest rates (e.g., Cole et al. 1994). It is then interesting to compare, as a function of redshift, the ratio of the space densities of galaxies forming stars at rates in excess of, say, 1 and $10 \text{ M}_\odot \text{ yr}^{-1}$. From the Gallego et al. (1995) $\text{H}\alpha$ survey, we estimate $n(>1 \text{ M}_\odot \text{ yr}^{-1})/n(>10 \text{ M}_\odot \text{ yr}^{-1}) \approx 50$ at the present epoch. A similar value is found to characterize, at $\langle z \rangle = 2.75$, the distribution of the SFRs of the F300W dropouts in the *HDF*. Thus, unless a substantial fraction of the modest star-forming galaxies at these early times are red either because they are relatively old or because they are reddened by dust, there seems to be little evidence in our sample for a large enhancement of their space density relative to the abundance of highly star-forming objects.

5.3 Chemical enrichment of the intergalactic medium

There is one piece of evidence pointing towards a metal ejection density at $z \gtrsim 3$ that is at least as large as that derived in equation (22), namely the observations of a significant cosmological mass density of metals associated with QSO absorption systems at high redshift. We will focus here on the numerous $\text{Ly}\alpha$ forest clouds. Recent spectra at high S/N ratio and high resolution obtained with the Keck telescope (Tytler et al. 1995; Cowie et al. 1995) have shown that 50–60 per cent of the $\text{Ly}\alpha$ clouds with $\log N_{\text{H I}} > 14.5$ have undergone some chemical enrichment, as evidence by weak, but measurable, C IV absorption lines. The typical inferred metallicities, Z_{IGM} , range from times 0.003 to times 0.01 of the solar values, subject to the uncertainties of photoionization models. Because the $\text{Ly}\alpha$ clouds have large filling factors and contain a significant fraction of the baryons in the Universe, the new data are strong evidence for a widespread distribution of metals in the IGM. These metals may have been produced *in situ* or in dense gaseous regions of galaxies; the metal-enriched gas was then expelled from the regions of star formation to large distances consistent with the sizes of the $\text{Ly}\alpha$ clouds.

Associated with the latter type of enrichment a characteristic MER density can be estimated as

$$\dot{\rho}_{Z, \text{IGM}}(3) \approx (4 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}) \times \left(\frac{\Omega_{\text{IGM}}}{0.05} \right) \left(\frac{Z_{\text{IGM}}}{0.005 Z_\odot} \right) \left(\frac{f_{\text{inj}}}{0.5} \right)^{-1} \left(\frac{\Delta t}{t_{\text{H}}} \right)^{-1}, \quad (25)$$

where Ω_{IGM} is the baryonic density parameter of the $\text{Ly}\alpha$ cloud phase, f_{inj} is the fraction of heavy elements injected into the IGM during a time-scale Δt , and t_{H} is the Hubble time at $z=3$. If QSO absorption systems trace the bulk of star formation occurring in galaxies at high redshifts (Lanzetta, Wolfe & Turnshek 1995; Pei & Fall 1995; Madau

& Shull 1996), it is therefore plausible that a population of dwarf galaxies, actively forming stars at $z \gtrsim 3$ at a rate comparable to the limit inferred from the *HDF* data, may be responsible for the contamination of the IGM at high redshifts. Such galaxies have shallow gravitational potential wells, thus allowing easy ejection of the heavy elements produced during their active star-forming phase.

5.4 The ionizing background at $z \gtrsim 4$

In the last few years growing evidence has accumulated on the existence of a significant decline in the space density of bright QSOs beyond $z \sim 3$ (Schneider, Schmidt & Gunn 1994; Warren, Hewett & Osmer 1994; Kennefick, Djorgovski & de Carvalho 1995). This shortfall, estimated to be about a factor of 5, poses serious problems to the idea that a quasar-dominated UV background is responsible for maintaining the intergalactic gas in a highly ionized state above $z \sim 4$ (e.g., Haardt & Madau 1996). It may be of some interest, in this context, to speculate on the possible contribution of our population of star-forming ‘spheroids’ to the metagalactic flux at early epochs (see also Songaila et al. 1990). A minimum value for the intensity of the ionizing background at $z = 4$ is given by

$$J_L(4) = \frac{hc}{4\pi} n_{\text{H,crit}}(4) \Omega_{\text{IGM}} \\ \approx 2.4 \times 10^{-22} \left(\frac{\Omega_{\text{IGM}}}{0.05} \right) \text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}, \quad (26)$$

where $n_{\text{H,crit}}$ is the closure hydrogen density. This equation reflects the underlying physics of the ionization process: ignoring recombinations, at least one UV photon is required per hydrogen atom to photoionize the IGM. The ionizing radiation flux is largely local, as sources at higher redshifts are severely absorbed by intervening clouds. At $z = 4$, the attenuation length is only $\Delta l \approx 13$ Mpc (Madau 1992). The required (proper) volume emissivity at 1 Ryd (where 1 Ryd = 13.6 eV) is then $4\pi J_L / \Delta l$. Collecting, and converting as usual, an ionizing luminosity density into an MER per unit comoving volume, we obtain

$$\dot{\rho}_{z,\text{ion}}(4) \approx (2 \times 10^{-4} \text{M}_{\odot} \text{yr}^{-1} \text{Mpc}^{-3}) \left(\frac{\Omega_{\text{IGM}}}{0.05} \right) \left(\frac{f_{\text{esc}}}{0.5} \right)^{-1}, \quad (27)$$

where now f_{esc} is the escape fraction into the IGM of Lyman continuum photons. A comparison between equations (23) and (27) provides some rationale for the hypothesis that a population of galaxies at $z \sim 4$, production of metals at a rate that is a few times higher than the lower limit derived from the *HDF* data, might rival quasars as a source of photoionization of the IGM. Larger star formation rates would be required if a significant fraction of the UV radiation emitted from stars cannot escape into the intergalactic space, $f_{\text{esc}} \ll 1$.

ACKNOWLEDGMENTS

We have benefited from discussions with M. Fall, D. Hogg, C. Leitherer, S. Lilly, Y. Pei, M. Pettini and M. Shull.

Support for this work, which was based on observations made with the NASA/ESA *Hubble Space Telescope*, was provided by NASA through grant AR-06337.10-94A from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. MG acknowledges support from the Hubble Fellowship program through grant number HF-01071.01-94A. CCS acknowledges support from the Sloan Foundation and from the NSF through grant AST-9457446.

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